Spectral State Transitions in Aql X-1: Evidence for 'Propeller' Effects

S. N. Zhang[1,2], W. Yu[1,4], W. Zhang[3]

[1]ES-84, NASA/Marshall Space Flight Center, Huntsville, AL 35812, USA

[2]Universities Space Research Association

[3]NASA/GSFC, Code 662, Greenbelt, MD 20771

[4]LCRHEA, Institute of High Energy Physics, Beijing, China

Received ____________________; accepted ____________________

ABSTRACT

Aql X-1 is a soft X-ray transient source and emits type I X-ray bursts. A spectral state transition was observed with RXTE during its outburst decay in February and March 1997. Its 10-30 keV and 5-10 keV count rate ratio increased suddenly when its luminosity was between (4-12) E35 ergs/s, assuming a 2.5 kpc distance. Spectral fitting with a model composed of a blackbody and a power-law components showed that its blackbody component decreased and the power-law became much harder significantly and simultaneously. We interpret this transition as caused by the centrifugal barrier, or commonly known as the 'propeller' effect. We thus infer that the magnetic field strength of the neutron star is around 1E8 Gauss, if the neutron star spin period is 1.8 ms. Similarly we infer the neutron star magnetic field strength in another soft X-ray transient Cen X-4 is about 2E9 Gauss. We also propose a unified scheme for spectral state transitions in soft X-ray transients, from soft high state to hard low state and further to quiescent state. With this scheme accretion onto neutron star may take place even during the propeller regime.

Subject headings: stars: individual (Aql X-1, Cen X-4) – X-rays: stars and neutron star physics and accretion disks

1. Introduction

Aql X-1 is a soft X-ray transient (SXT) with rather frequent outbursts (see for example, Priedhorsky & Terrell 1984; Kitamoto *et al.* 1993; Harmon *et al.* 1996). It is believed to contain a weakly magnetized neutron star (NS) as indicated by its type I X-ray bursts (Koyama *et al.* 1980; Czerny, Czerny & Grindlay 1987). From the observed 549 Hz oscillations of X-ray flux during one of its X-ray bursts, its NS is believed to be spinning at a period (P) of either 1.8 or 3.6 ms (White & Zhang 1997, Zhang *et al.* 1997), thus among the fastest spinning NS known. The strength of its magnetic field (B) has never been determined from observations, although believed to be quite weak, as inferred from the lack of any detectable pulsed X-ray flux in its persistent emission.

Aql X-1 has been observed to exhibit three types of X-ray spectral states. When its luminosity is above $\sim 10^{36}$ ergs/s (assuming a distance of 2.5 kpc), its spectrum is very soft (Czerny, Czerny & Grindlay 1986). Just below this luminosity level, its spectrum is dominated by a much harder power-law component and the blackbody (BB) component becomes almost undetectable above 2-3 keV (Czerny, Czerny & Grindlay 1987; Harmon *et al.* 1996). At even lower Lx ($\sim 10^{33}$ ergs/s), its spectrum again is dominated by a BB component (Verbunt *et al.* 1994).

In this paper, we report a clear spectral state transition in Aql X-1 detected with RXTE in February and March 1997 during an outburst decay. We propose that the soft to hard state transition in Aql X-1 is due to the centrifugal barrier, also commonly known as the 'propeller' effect.

2. Observations and Results

We followed the decay phase of the outburst of Aql X-1 in February and March 1997 with RXTE (Bradt, Rothschild & Swank 1993), as shown in figure 1. The hardness ratio (between the PCA count rates in 10-30 and 5-10 keV bands) remained remarkably stable during the first 17 days of observations until near the end of the outburst decay between MJD 50510 and 50512 (March 5, 1997), when the hardness ratio increased suddenly.

We performed a spectral analysis for the last several days of observations, as listed in table 1. Since the spectral model consisting of a BB component plus a power-law component has been applied successfully to the spectra of Aql X-1 (Czerny, Czerny & Grindlay 1986) and other similar NS SXTs, for example, 4U1608-52 (Mitsuda *et al.* 1984, 1989), we also adopted this spectral model to the RXTE/PCA data. An iron line feature is also included.

It can be seen clearly that after around MJD 50510 (March 3, 1997) (figure 1), the BB component luminosity within the total luminosity decreased significantly and the power-law became much harder in the meantime. The spectral state transition luminosity is between (4-12)$\times 10^{36}$, assuming a distance of 2.5 kpc.

3. A Unified Model for Soft X-ray Transients

3.1. Soft State or Regular Accretion State

The radius of the NS magnetosphere (R_m) varies slowly with the mass accretion rate ($\dot{M}$) onto the neutron star (Lamb, Pethick & Pines 1973; Cui 1997):

$$R_m = 10^7 L_{x,36}^{-2/7} M_{1.4}^{1/7} B_9^{-4/7} R_6^{10/7} \mathrm{cm} \tag{1}$$

where $L_{x,36}$ is the bolometric X-ray luminosity in 10^{36} ergs/s, B_9 is the NS magnetic field strength in units of 10^9 G, $M_{1.4}$ is the NS mass in units of 1.4 $M_\odot$, and R_6 is its radius in units of 10 km.

When $\dot{M}$ is so high that R_m is smaller than the last stable orbit ($3R_S$=$\frac{6GM}{c^2}$, where M is the NS mass) of the NS, the inner disk radius (R_{in}) is $3R_S$ (the recently detected kilohertz QPOs imply that the NSs are indeed within their last stable orbit; see for example Kaaret, Ford & Chen 1997, Miller, Lamb & Psaltis 1996 and Zhang, Strohmayer & Swank 1997). In this state both the inner accretion disk and the NS surface produce BB emissions with a characteristic temperature of $\sim$ 1 keV (see, for example, Mitsuda *et al.* 1989). A hard X-ray power-law component may be produced via Comptonization of the BB emission photons by the bulk motion of the relativistic inflow from the last stable orbit towards the NS surface (Hanawa 1991, Kluzniak & Wilson 1991, Walter 1992). Therefore its continuum spectrum is made of a soft BB component plus a power-law.

The magnetosphere will expand when $\dot{M}$ decreases. When $R_m > 3R_S$, then $R_{in} = R_m$. When $R_m > 3R_S$ *and* R_m is smaller than the corotation radius (R_C), (almost) all the material transferred from the companion falls onto the NS surface. The overall spectral shape should remain basically unchanged. This should correspond to the constant hardness ratio during the decay phase of Aql X-1 outburst right before the sudden spectral transition.

In several similar NS systems, kilo-hertz OPOs have been detected previously. Such QPOs can be explained reasonably well within the frame work of some kind of beat frequency model, in which the higher and lower frequency QPOs

are the Keplerian frequency of the inner region of the disk and its beat frequency against the neutron star spin frequency, respectively (see van der Klis 1997 for a review). Assuming that the higher frequency QPOs are produced as a result of the interaction between the magnetosphere and the inner accretion disk boundary, we would then expect that when the magnetosphere is inside the peak emission radius of the inner accretion disk region, no kilo-hertz QPOs are detectable. The peak radius is roughly 1.4 times the radius of the last (marginal) stable orbit of the NS (Zhang, Cui & Chen 1997). Therefore B can also be estimated from the luminosity for the first appearance of its kilo-hertz QPOs, i.e, the highest QPO frequency, of the source during a luminosity decay, using the relation $R_m = 1.4 \times 3R_S$. In a companion paper (Zhang *et al.* 1997), the luminosity of Aql X-1 is reported to be $\sim 2\times10^{36}$ ergs/s when kilo-hertz QPOs were detected. Thus the inferred strength of the NS magnetosphere is $\sim 0.7\times10^{8}$ G.

When $R_C > R_m > 1.4 \times 3R_S$, the QPO frequency and the X-ray luminosity (Lx) should be correlated positively. The exact correlation depends upon the structure of the accretion disk just outside the magnetosphere. When the vertical structure of the inner accretion disk region changes, the relationship between the QPOs and $\dot{M}$ will also change accordingly. Such evidence has been reported by some of us for the same Aql X-1 outburst decay (Zhang *et al.* 1997).

3.2. Hard State or Propeller State

When $R_m > 3R_S$ *and* $R_m > R_C$, the accreted material can no longer overcome the centrifugal barrier, thus the mass accretion onto the surface will be reduced substantially. This is the well known ‘propeller’ effect (Illarionov

& Sunyaev 1975) Stella, White and Rosner (1986) pointed out that 'propeller' effects might be responsible for the transient nature of many pulsars. Such evidence has been reported in two X-ray pulsars GX1+4 and GROJ1744-28 (Cui 1997), when their pulsed emission disappeared suddenly during their decay phases. The inferred values of B are $>10^{13}$ G and $\sim 2\times10^{11}$ G for GX1+4 and GROJ1744-28, respectively.

When the propeller effects take place in a weakly magnetized ($B < 10^9$ G) NS X-ray binary (the X-ray flux is usually not pulsed), the flux of the BB component from the NS surface should decrease significantly. In the meantime the BB component in the X-ray range from the inner accretion disk edge should also decrease significantly, since the inner disk region is disrupted by the NS magnetosphere. Therefore the overall BB flux should decrease significantly.

The power-law component should become much harder in the meantime. One reason is that the cooling effect of the BB photons from the NS surface and the inner disk BB emission should become much weaker, since thermal comptonization of these low energy photons by hot electrons has been regarded as the primary mechanism for the hard X-ray power-law production (see for example a recent review by Tavani and Barret (1997) and references therein). The other is that the plasma just outside the magnetosphere will become very hot in the propeller regime (Wang & Robertson 1985), thus will make the power-law component even harder. As a consequence, the BB component will decrease suddenly and the power-law will become much harder.

Additional hard X-ray emission may also be produced by the relativistic outflow as a result of the propeller effects. For a 1.8 or 3.6 ms NS, the Keplerian velocity at the corotation radius is $0.29c$ and $0.23c$, respectively. Thus the outflow is certainly relativistic. Inverse Compton scattering of low energy

photons by the bulk motion of the outflow may also be responsible for the power-law hard X-ray production, in a similar way as the suggested hard X-ray production by the bulk motion of the accreted material *towards* the NS (Hanawa 1991, Kluzniak & Wilson 1991, Walter 1992).

We therefore identify the sharp spectral transition between MJD 50510 and 50512 is due to the expected propeller effects. The critical luminosity corresponding to the appearance of the expected propeller effect is (Lamb, Pethick & Pines 1973; Cui 1997):

$$L_{x,36} \approx 2.34 B_9^2 P_{-2}^{-7/3} M_{1.4}^{-2/3} R_6^5 \tag{2}$$

where P_{-2} is the spin period in units of 10 ms. Assuming the NS mass of 1.4 $M_\odot$ and a neutron star radius of 10^6 cm, the inferred value of B is thus $(1.5-2.5)\times 10^8$ G or $(0.7-1.1)\times 10^8$ G for $L_x=(4-12)\times 10^{35}$ ergs/s, corresponding to P=3.6 ms or 1.8 ms, respectively. Considering the consistency with the value of B estimated from the first appearance of QPOs, *the most likely value of* B *is* $\sim 10^8$ *G and* P*=1.8 ms, i.e., the observed 549 Hz oscillation frequency is the NS spin frequency rather than one of its harmonic frequencies.* We note that the uncertainty in estimating R_m (Wang 1996) does not affect the above consistency comparison, since we applied the same equation from Lamb, Pethick & Pines (1973) in both cases, so that the uncertainty is cancelled out. Similar spectral state transitions were also observed in Cen X-4 at a luminosity level of $\sim 8\times 10^{35}$ ergs/s (Bouchacourt *et al.* 1984). Then $B\sim 2\times 10^9$ G, if $P\sim 33$ ms (Mitsuda *et al.* 1996). In figure 2 we plot the relationship between B and L_x for different values of P. The locations of two X-ray pulsars (GX1+4 and GROJ1744-28, from Cui 1997) and two soft X-ray transients (Aql X-1 and Cen X-4) are also marked.

The exponential decay constant (e-folding time) of the outburst is $\sim$20 days.

The amount of decay expected in two days would have caused a luminosity decrease by $\sim$10%. Therefore the observed sudden BB luminosity decrease implies that $\gtrsim$90% of the material is 'propelled' out and only $\lesssim$10% of the material reached the NS surface. We note here that whether one uses the total flux or just the BB flux to estimate the change in $\dot{M}$ after the spectral transition does not qualitatively change this conclusion.

It is also interesting to check the consistency of our above interpretation with the model of Wang and Robertson (1985). Using B=10^8 G and $\dot{M}$=10^{-12} $M_\odot$/year (corresponding to 10^{36} ergs/s for a 20% rest mass conversion efficiency) and taking all three factors used in their equations (30), (33) and (35) to be unity, we obtain the equilibrium period of the NS to be $\sim$2 ms, the mean plasma temperature just outside the boundary layer of the magnetosphere to be $\sim 2\times10^9$ K (kT $\sim$170 keV), and the maximum energy of the non-thermal particles produced within the neutral sheets located at the boundaries of the vortex structures to be $\sim 4\times10^{15}$ eV. It is interesting to note that for a similar spectrum in a similar system 4U1608-52, the inferred kT from an observed broken power-law is $\sim$65 keV (Zhang *et al.* 1996). The possibility of producing high energy particles implies that SXTs in the propeller phase may be gamma-ray emitters.

In this state we also expect that the kilo-Hertz QPOs will cease to exist or become much weaker. This could be an additional indicator of the on-set of the propeller phase. In fact for Aql X-1, high frequency QPOs became undetectable just before the observed spectral state transition, or the propeller effects take place.

3.3. Quiescent or Advection Dominated States

When $\dot{M}$ decreases further, the disk itself becomes advection dominated and its entire optically thick inner region is truncated (Narayan 1996; Hameury *et al.* 1997). The radius at which the rotation velocity of the NS magnetosphere reaches the speed of light is $\sim 10^{7-8}$ cm for millisecond spinning NSs, still very close to the NS surface. Thus the inner boundary of an advection dominated disk ($>10^{9-10}$ cm) is very far away from the NS magnetosphere. In this case, the mass transfer from the outer accretion disk onto the NS should be nearly spherical. Therefore some infalling matter can escape the centrifugal barrier and falls onto the polar regions of the NS to produce the observed weak BB luminosity. The inferred small radii of the BB emission regions in the quiescent states of several SXTs (Verbunt *et al.* 1994; Asai *et al.* 1996) also agree with this picture. In some cases, X-ray pulsations are expected, if the NS spin and the magnetic field axis are mis-aligned and that X-ray emission regions cover only part of the NS surface. Indeed weak X-ray pulsations were reported in a similar system Cen X-4 during its quiescent state (Mitsuda *et al.* 1996). It is also interesting to note that Cen X-4 is so far the only NS SXT possibly observed with X-ray pulsations in the quiescent state, and yet its inferred value of $B \sim 2\times 10^9$ G may be near the upper end of the expected value for type-I X-ray bursters (see for example, Joss 1978; Taam & Picklum 1978; Joss & Li 1980). A hard power-law component may also be produced, again due to the relativistic outflows. In this case the seed photons available for inverse Compton scattering are much less populous than when the system just enters the propeller state, since the advection dominated outer disk is cold and does not produce much radiation.

In our model the propeller and quiescent state properties of SXTs are

different from previous models of Stella *et al.* 1994 and Verbunt *et al.* 1994. Verbunt *et al.* (1994) argued that a detection of any significant X-ray flux (more than the level possible from the low mass companion star) in a X-ray binary system implies that the system is *not* in its propeller regime. In the model of Stella *et al.* (1994), accretion onto the neutron star surface is also not possible in the propeller regime, but UV or soft X-ray emission is possible at the magnetospheric radius. In our model, X-ray emission and the observed spectral shape in the propeller or an even lower accretion rate state – the quiescent state are very natural. We emphasize that the major difference between our model and the previous ones is that *in the quiescent state of our model, the disk is truncated, due to the advection dominance, very far away from the light cylinder of the neutron star magnetosphere.* Thus near-spherical accretion onto the neutron star poles are possible. We predict that *some SXTs in quiescence should be millisecond X-ray pulsars.*

As this paper is ready for submission, we learnt that another paper by Campana *et al.* (1997) is near its completion for submission. In that independent paper, Campana *et al.* report a rapid luminosity decrease of Aql X-1 around and after the spectral state transition reported in this paper, from the SAX/NFIs observations during the same outburst decay. They arrived at almost identical conclusions concerning the transition to ours in this paper.

Acknowledgement: SNZ appreciates deeply the many stimulating discussions with Wei Cui, Wan Chen and Marco Tavani, which initially brought his attention to this topic. The anonymous referee is highly appraised for his/her prompt response and providing many valuable suggestions and constructive criticism, which certainly improved the overall quality of this paper. We also thank Didier Barret, Luigi Stella and Marco Tavani for making useful comments on the

manuscript. SNZ also acknowledges partial financial support by NASA through contracts NAG5-3681, 4411 and 4423.

REFERENCES

Asai, K. *et al.* 1996, PASJ, 48, 257

Bouchacourt, P. *et al.* 1984, ApJ, 285, L67

Bradt, H.V., Rothschild, R.E. & Swank, J.H. 1993, A&AS, 97, 355

Campana, S. *et al.* 1997, Nature, to be submitted.

Cui, W. 1997, ApJ, 482, L163

Czerny, M., Czerny, B. & Grindlay, J.E. 1987, ApJ, 312, 122

Hameury, J.-M. *et al.* 1997, ApJ, in press

Hanawa, I. 1991, ApJ, 373, 222

Illarionov, A.F., & Sunyaev, R.A. 1975, A&A, 39, 185

Joss, P.C. 1978, ApJ, 225, L123

Joss, P.C. & Li, F.K. 1980, ApJ, 238, 700

Kaaret, P., Ford, E. & Chen, K. 1997, ApJ, 480, L27

Kitamoto, S. *et al.* 1993, ApJ, 403, 315

Kluzniak, W. & Wilson, J. 1991, ApJ, 372, L87

Koyama, K. *et al.* 1981, ApJ, 247, L27

Lamb, F.K., Pethick, C.J., and Pines, D. 1973, ApJ, 184, 271

Mitsuda, K. *et al.* 1984, PASJ, 36, 741

Mitsuda, K. *et al.* 1989, PASJ, 41, 97

Mitsuda, K. *et al.* 1996, in 'X-ray Imaging and Spectroscopy of Cosmic Hot Plasmas', ed. F. Makino & K. Mitsuda (Universal Academy Press, Inc. – Tokyo, Japan).

Narayan, R. 1997, in ‘Accretion Phenomena and Related Outflows’, ed. D.T. Wickramasinghe, G.V. Bicknell & L. Ferrario, ASP Conf. Series Vol 121

Priedhorsky, W.C. & Terrell, J. 1984, ApJ, 280, 661

Stella, L. *et al.* 1994, ApJ, 423, L47

Stella, L., White, N.E. & Rosner, R. 1986, ApJ, 308, 669

Taam, R.E. & Picklum, R.E. 1978, ApJ, 224, 210

Tavani, M. & Barret, D., in the Proceedings of the Fourth Compton Symposium, Willamsburg, VA, April 1997

Walker, M. 1992, ApJ, 385, 661

Wang, Y.-M. & Robertson, J.A. 1985, A&A, 151, 361

Wang, Y.-M. 1996, ApJ, 465, L111

White, N.E. & Zhang, W. 1997, ApJ Lett. in press

Zhang, S.N. *et al.* 1996, 120C, 279

Zhang, W., Strohmayer, T.E. & Swank, J.H. 1997, ApJ, 482, L167

Zhang, W. *et al.* 1997, submitted to ApJ

Verbunt, E. *et al.* 1994, A&A, 285, 903

van der Klis, M., in the Proceedings of the Wise Observatory 25th Anniversary Symposium ”Astronomical Time Series”, Tel Aviv, January 1997

This manuscript was prepared with the AAS LaTeX macros v4.0.

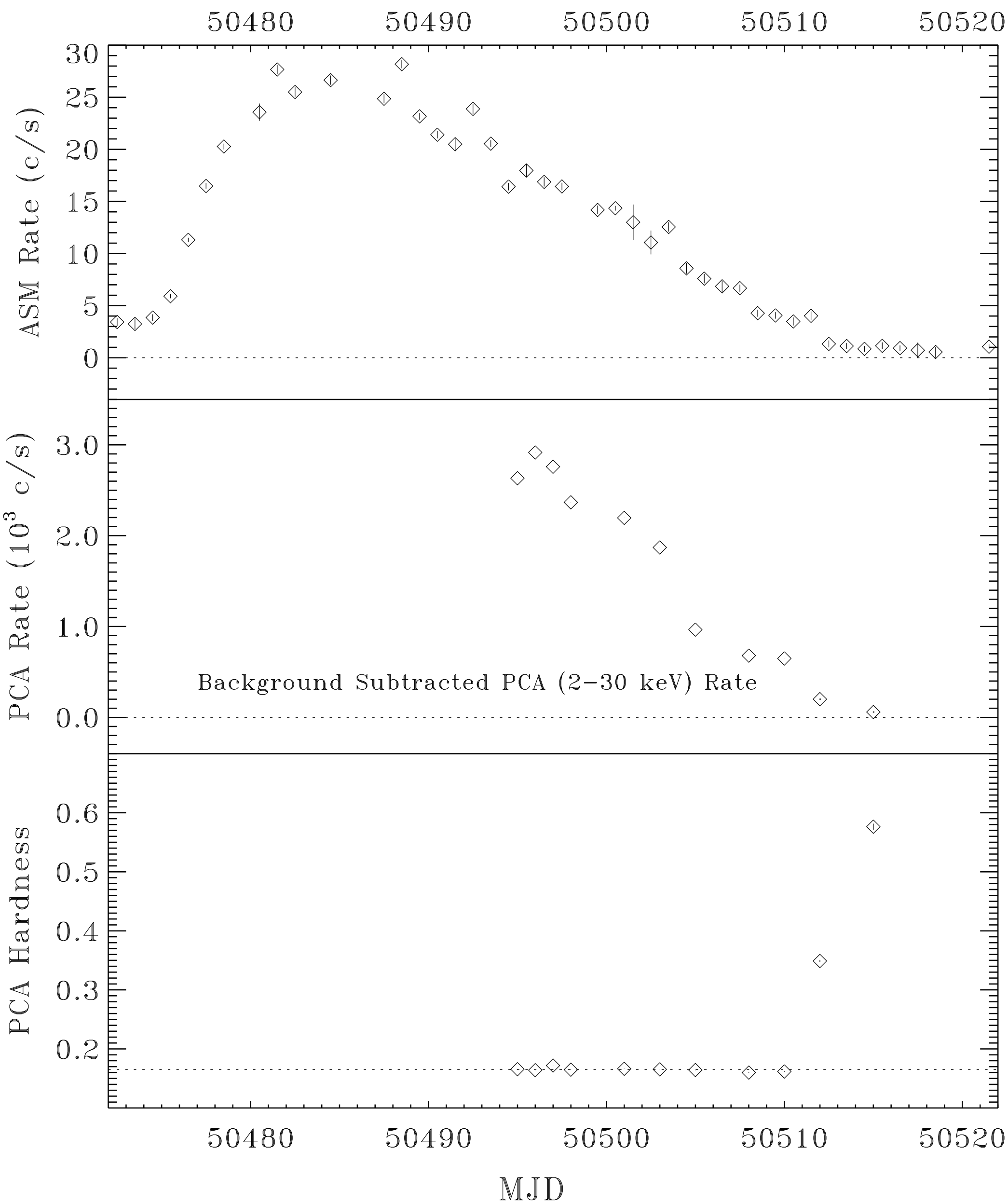

Fig. 1.— Spectral evolution of Aql X-1 during its outburst decay phase. The hardness ratio (10-30/5-10 keV) remained as almost a constant when the PCA count rate decreased from about 3000 c/s to about 700 c/s and then suddenly increased significantly when the count rate was around and below 200 c/s.

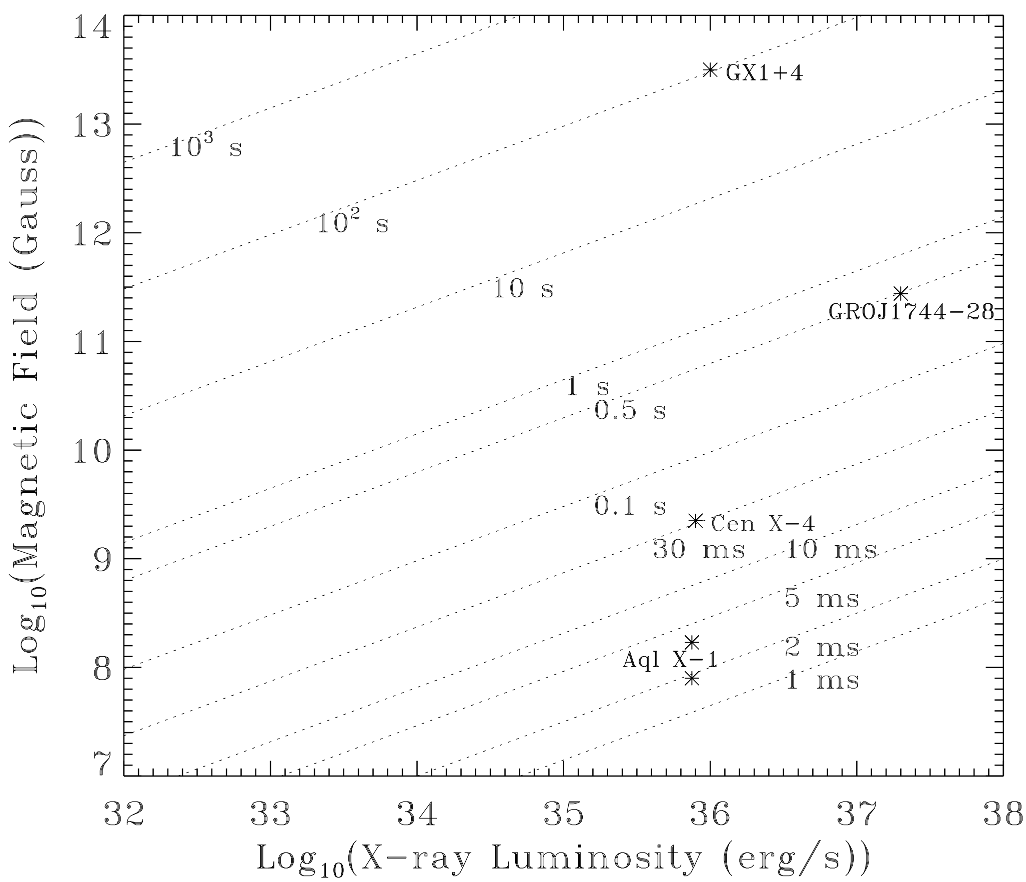

Fig. 2.— Relationship between the neutron star magnetic field strength and the critical luminosity level at which the propeller effect takes place. The locations of GX1+4, GROJ1744-28, Aql X-1 and Cen X-4 are also marked.

Obs.	Power Law		Blackbody		6.4 keV Iron Line		Total	$\frac{\mathrm{BB}}{\mathrm{Total}}$	$\frac{\chi^2}{39}$
	Index	Norm	kT_{bb}	L_{bb}	1-σ Width	Flux	L_x		
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)
09	3.26±.01	1.96±.04	1.51±.01	5.37±.04	.59±.05	11.±1.	1.47	.37	2.49
10	2.29±.02	.20±.01	1.17±.04	.43±.02	.87±.05	10.±1.	0.45	.10	1.37
11	1.83±.03	.028±.002	.50±.03	.32±.04	.33±.20	.80±.30	0.15	.21	1.10

Table 1: Model spectral fitting results for the last three observations shown in figure 1. PCA data between 3-20 keV are used ($N_H = 3.3E21/cm^2$). *Notes:* (1) No. 09: MJD 50509.906–50510.025, No. 10: 50511.951–50512.062, No. 11: 50514.892–50515.055; (2) Photon spectral index; (3) photon/keV/cm^2/s at 1 keV; (4) keV; (5) 10^{35} ergs/s at 2.5 kpc; (6) keV; (7) 10^{-4} photon/cm^2/s in the line; (8) 1.5-30 keV, 10^{36} ergs/s at 2.5 kpc.